IC/95/147

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SEISMOTECTONIC MODELS AND CN ALGORITHM: THE CASE OF ITALY

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ABSTRACT

The CN algorithm is here utilized both for the intermediate term earthquake prediction and to validate the seismotectonic model of the Italian territory. Using the results of the analysis, made through the CN algorithm and taking into account the seismotectonic model, three areas, one for Northern Italy, one for Central Italy and one for Southern Italy, are defined. Two transition areas, between the three main areas are delineated. The earthquakes which occurred in these two areas contribute to the percursor phenomena identified by the CN algorithm in each main area.

MIRAMARE – TRIESTE

July 1995

1. INTRODUCTION

The analysis of the Time of Increased Probability (TIP) of a strong earthquake with magnitude greater than, or equal to a given threshold M_0, based on the algorithm CN, makes use of normalized functions, which describe the seismicity pattern of the analyzed area. Therefore the original algorithm, developed for the California-Nevada region, can be directly applied, without any adjustment, in areas with different size and level of seismicity.

It has been shown by Costa et al. (1995) that a regionalization, supported by seismological and tectonic arguments, leads to the reduction of the alarm duration (TIP) and of the failures to predict, and increases the stability of the algorithm. Therefore, the CN algorithm permits to deal with the development of modern regional geodynamic models, involving relationships between the key structural features which control the seismicity, and the selection of the optimal causative fault system for prediction purposes (Rundkvist and Rotwain, 1995).

The algorithm CN is described in full detail by Gabrielov et al. (1986) and Keilis-Borok and Rotwain (1990). An application to Central Italy is given by Keilis-Borok et al. (1990), where the borders of the studied area were defined simply according to the completeness of the used catalogue. The analysis of the seismicity and seismotectonic considerations permitted the definition of a more detailed regionalization of Central Italy and to test the stability of the method (Costa et al., 1995).

In the present study the analysis is extended to the whole Italian territory. Using the seismotectonic model of Italy (Patacca et al., 1990) and the spatial distribution of the epicenters (Fig. 1), the country is divided into three main areas (Fig. 2). Each of them is characterized by a dominant seismotectonic behavior, with varying seismicity pattern, therefore the appropriate M_0 is used in each area.

The catalogue used routinely for the application of the CN algorithm in Italy has been compiled in the following way. For the period 1900-1979 the PFG catalogue has been adopted (Postpischl, 1985) and whereas the ING (Istituto Nazionale di Geofisica, 1994) catalogue has been used thereafter. This catalogue hereafter is referred to as PFGING. M_I (magnitude from intensity), M_d (duration magnitude) and M_L (local magnitude) are available in this catalogue.

2. GEODYNAMIC OUTLINE

The Italian territory can be divided in three main tectonics areas (Northern, Central, and Southern Italy) with different types of recent motion (Patacca and Scandone, 1989; Dal Piaz and Polino, 1989). Each of these main areas is subdivided into several smaller seismogenic zones with different seismotectonic characteristics and behavior (Fig. 1).

The first area, Northern Italy (north of 44° N), is characterized by the presence of the Alpine arc, which is generally uplifting (Mueller, 1982). The eastern part of the area (Friuli), where one of the branches of the Southern Alps turns to the South along the Adriatic sea (Dinaric Alps), the western part of the area and the areas of contact between the Southern Alps and the Northern Apennines are characterized by compression (Dal Piaz and Polino, 1989). In the Friuli zone some strike-slip motion in the western direction is present too (Pavoni et al., 1992). Therefore, in Northern Italy the majority of the small zones are compressive or transpressive (Fig. 1).

In Central Italy two arcs of tectonic shortening, the North-Central Apennines and the Calabrian arc, meet. According to Patacca and Scandone (1989) the deformation in this area has been strictly controlled by the sinking of the foreland lithosphere beneath the mountain chain peninsula and not directly by the collision between Europe and Africa. This hypothesis is strongly supported by surface waves dispersion measurements (Calcagnile and Panza, 1981; Panza et al., 1982; Suhadolc and Panza, 1988), and other more recent investigations (Della Vedova et al., 1991; Marson et al., 1995). The North-Central Apennines arc can be divided in two main structures, parallel to its axis: the first one is a zone of compression, and

the second one is a zone of extension (Fig. 1). These two main structures are crossed by few transfer zones. Previous studies (Costa et al., 1991, 1995), have shown that the zones of extension and compression in Central Italy should not to be considered together in the regionalization.

According to Patacca et al. (1990), the 41° N parallel divides the Apennines chain in two completely different tectonic domains, and this line is proposed to separate Central from Southern Italy. The division of the Apennines into two major arcs may be related to the different sinking of the foreland lithosphere in the Northern Apennines and in the Calabrian Arc (Marson et al., 1995). The passive subduction of the Po-Adriatic-Ionian lithosphere, caused by gravitational sinking, appears as a reasonable mechanism to explain contemporaneous geodynamic events such as mountain building in the Apennines and the extension in the Tyrrhenian area.

Southern Italy is characterized by very complex tectonics and different seismotectonic zones with extensive, transfer, foreland and volcanic character can be recognized. The complexity here is even increased by the presence of several intermediate and deep focus earthquakes (Caputo et al., 1970), related to the Calabrian arc (Eastern Sicily, Calabria). This arc, which is the most important tectonic structure in Southern Italy, is an old subduction zone, where the deep-focus earthquakes are related to the existence of a lithospheric slab which may represent, in its deepest parts, the remnant of the Adriatic lithosphere which subducted Corsica-Sardinia before the opening of the Tyrrhenian sea (Patacca and Scandone, 1989).

3. REGIONALIZATION

To minimize the spatial uncertainity, the area where a strong earthquake has to be predicted, should be as small as possible, but there are two rules that limit its minimum dimensions: 1) the border of the area must be drawn following as much as possible the minima in the seismic activity; 2) the annual number of earthquakes with magnitude greater or equal to the completeness threshold of the catalogue has to be greater or equal to 3.

The borders between the three main areas: Northern, Central and Southern, described in Chapter 2, are not sharply defined and they can be better represented by a transition domain. In fact, as we will see, the division of the Italian territory in three main areas, separated by two transition areas, seems to be consistent with the indications given about the properties of seismicity by the CN algorithm. A synopthic representation of the different areas is given in Fig. 2, while the shapes of the two variants of each main area are given in Fig. 3.

3.1. NORTHERN ITALY

The Alpine arc, the most important tectonic feature in Northern Italy, is crossed by different political borders and consequently the catalogue PFGING is fairly incomplete for our purposes. To fill in the gap it was necessary to add the information contained in two other catalogues: ALPOR (1987) and NEIC (1992). ALPOR is the catalogue of the Eastern Alps, compiled at the Osservatorio Geofisico Sperimentale, Trieste, Italy. In this catalogue there are reported two magnitudes: M_I and M_L. NEIC is the catalogue of the National Earthquake Information Center (NEIC, USGS, Denver, USA). In this catalogue are reported the body wave magnitude, m_b, the surface wave magnitude, M_S, and M_L.

The catalogue that we used in the application of the CN algorithm in Northern Italy is obtained merging ALPOR, PFGING and NEIC. Taking into account the uncertainties, which are intrinsic in the three different catalogues considered, the events differing in origin time by less than 1 minute and in epicentral location by less than 0.5° , both in latitude and longitude, are considered the same event. The priority in the choice of the magnitude to be used in the further processing is given in Table 1. The aftershocks are eliminated, using the criteria given by Keilis-Borok et al. (1980), and only the events with magnitude greater than, or equal to 3 have been used.

According to the standards used in the CN algorithm (Costa et al., 1995), the magnitude threshold for the definition of the strong earthquakes is chosen to be M_o=5.4. In the present study the period 1960-1992 is analyzed, because of the significant incompleteness of the catalogue before 1960. In the region only 2 strong earthquakes occurred during the last 30 years (M=6.5, May 6, 1976 and M=5.4, January 2, 1988). The M=6.0 September 15 1976 event is a strong aftershock, identified as Related Strong Earthquake by Vorobieva and Panza (1993), and therefore it is not a target in the CN algorithm.

There are two important tectonic features in Northern Italy: the intersection of the Alps and the Dinarides in Friuli and the intersection of the Alps and the Apennines in Liguria. Because of the complexity of the region, it is rather difficult to define the appropriate borders of the area to be considered for the purposes of the CN algorithm. To solve this problem it has been formulated the hypothesis that the stress, responsible of earthquake occurrence, "propagates" along a major fault or tectonic structure and "accumulates" at the edges of this structure, and/or in the areas of intersection with other important faults or tectonic structures. Therefore, for the purposes of earthquake prediction, the events concentrated at the edges, or in the areas of intersections with other structures, of a given tectonic structure can not be considered independent and should all be contained in the same area. In the present study, the Alpine arc is considered as the structure along which the tectonic stress propagates, and the events concentrated on both of its edges, western and eastern, are assumed to be correlated, and therefore included in the same area.

The seismogenic region, thus defined, is shown in Fig. 3a. The two strong events are predicted and the TIP duration is 27% of the total time (see Fig 4a). There is only one false alarm after the strong earthquake of 1988.

In order to test the hypothesis that the earthquakes, concentrated on the edges of a tectonic structure or in the areas of intersection with other structures, cannot be neglected for the purposes of earthquake prediction, a second regionalization (Fig. 3b), which includes only the compressive domains in the Eastern Alps (Fig.

1) is considered. The two strong events are predicted (Fig 4b), but the TIP duration increases to 34% of the total time, and there are 3 false alarms.

3.2. SOUTHERN ITALY

The used catalogue, PFGING can be considered complete in this part of Italy only after 1950, and for magnitude over 3. The magnitude threshold in the definition of the strong earthquakes has been chosen as M_0=6.5.

Following the idea of Patacca et al. (1990), that the 41° N parallel divides the Apennines into two completely different tectonic domains, for Southern Italy the area shown on Fig. 3c has been delineated. The results of the CN algorithm applied to this area are reported in Fig. 5a. All three strong earthquakes (M=7.6, November 23 1954, M=7.0 November 23, and M=6.9, November 24, both in 1980) are predicted and the duration of TIP is 33% of the total time. There are 5 false alarms.

To study the influence of the relevant deep seismicity we consider only the shallow earthquakes and thus the only strong event to be predicted is the M=7.0, November 23, 1980 earthquake. The diagnosis of the CN algorithm is given in Fig. 5b. The strong event is predicted, but the duration of TIP increases up to 44% of the total time and there are six false alarms. This result indicates that the shallow and the deep seismicity in this area are not independent, in contrast with that observed in other parts of the world (Keilis-Borok and Rotwain, 1990).

As a second test, according to the regionalization for Central Italy proposed by Costa et al. (1995), the northern border of Southern Italy was traced along the 39.5° parallel (Fig. 3d). In this area the two strong earthquakes to be predicted are the M=7.6, November 23, 1954 and the M=6.9, November 23, 1980 events. The 1980 earthquake is predicted with a TIP duration lasting for 25% of the total time; the 1954 M=7.6 event is a failure to predict and there are two false alarms (Fig. 5c).

3.3. CENTRAL ITALY

The CN algorithm has been initially applied to Central Italy (Keilis-Borok et al., 1990, Costa et al., 1995), because the catalogue PFGING is rather complete here. In the present study utilizing the regionalization shown in Fig. 3e, given by Costa et al. (1995), we extend the analysis up to the end of 1994 (Fig. 6a).

The definition of the areas in Northern and Southern Italy makes it necessary a revision of the regionalization of Central Italy. In fact, the regionalizations for Northern and Southern Italy, proposed in the present study, contain some zones (see Fig. 2), previously included in Central Italy (Costa et al., 1995). The new regionalization for this area is presented in Fig. 3f. Four strong earthquakes occurred in the area: M=5.8 and M=6.0, both on August 21, 1962, M=5.5, September 19, 1979 and M=5.4, May 7, 1984. As it can be seen from Fig. 6b, three out of the four strong earthquakes are predicted by the CN algorithm, while the 1979 event is a failure to predict; there are 4 false alarms and the TIPs increase, with respect to the previous study (Costa et al., 1995), from 30% to 38% of the total time.

Only the crustal earthquakes which occurred in Central Italy are used to obtain the results shown in Fig. 6. According to the model proposed by Marson et al. (1995) few intermediate and deep earthquakes belong to Central Italy and should be considered when using the CN algorithm. However, their inclusion in the data set does not affect the results, and it is not surprising since the number of these events and their size are small.

4. CONCLUSIONS

Habermann and Creamer (1994) analysed M8 (Keilis-Borok and Kosobokov, 1986), a prediction algorithm similar to CN, and showed that the algorithm preferentially identifies TIP's during periods of systematically increased magnitudes. The systematic increase of magnitudes has the same effect of changes in the completeness of the catalogue, used in the prediction. The analysis of the completeness of the PFGING catalogue, made by Molchan et al. (1995), allows us to state that the TIPs, diagnozed by the CN algorithm, cannot obviously be associated with the changes in the completeness level of the catalogue.

Three main areas in Italy (Northern, Central and Southern, each having a distinct seismicity pattern) have been analyzed in the present study, utilizing the CN algorithm. The separation among the three areas is not marked by sharp boundaries, and on the basis of different zonations, it is possible to identify intersection areas, which can be assigned to either bordering areas. The TIPs duration decreases in each area, when the intersection areas are included in it (Table 2). In Southern Italy, where a large number of intermetiate and deep focus events occur, all the earthquakes (shallow, intermediate and deep focus) should be used for the purposes of intermediate-term earthquake prediction.

ACKNOWLEDGMENTS

The authors are very grateful to Prof. V.I.Keilis-Borok for stimulating discussions. One of the authors (I.Rotwain) thanks ICTP for financial support for her stay in Trieste during which a large part of this work has been done. We acknowledge financial support from MURST (40% and 60%) funds and CNR-Gruppo Nazionale per la difesa dai Terremoti contracts n° 92.02867.54 and n° 93.02492.54.

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Table 1

Earthquakes catalogues used in Northern Italy.

CATALOG	PERIOD	MAGNITUDE	PRIORITY
PFGING	1000-1992	M_I, M_d, M_L	M_L, M_d, M_I
ALPOR	1000-1985	M_I, M_L	M_L, M_I
NEIC	1900-1992	m_b, M_s, M_L	M_L, M_s, m_b
FINAL	1900-1992	$M_{(ALPOR)}$, $M_{(PFGING)}$, $M_{(NEIC)}$	MAX

Notes:
The priority M_1, M_2, M_3 indicates that the magnitude M_1 has been used whenever available. If M_1 is not available, M_2 has been used etc.
MAX = Max(M_1, M_2, M_3)

Table 2

Final results

	Northern Italy		Southern Italy			Central Italy	
	Area 1	Area 2	Area 1	Area 1*	Area 2	Area 1	Area 2
events	2	2	3	1	2	3	4
predicted	2	2	3	1	1	3	3
false alarms	1	2	5	6	2	2	4
failures to predict	0	0	0	0	1	0	1
% di TIPs	27	34	33	44	25	23	38

(*) Only shallow events.

Figure captions

Figure 1. Seismotectonic model of Italy (Patacca et. al., 1990).

Figure 2. Seismicity map ($M \geq 4.0$) and boundaries of the three main areas in Italy. Dashed line marks variants of the regionalization.

Figure 3. Different regionalizations, considered in the present study: a) first variant considered in Northern Italy (area 1); b) second variant considered in Northern Italy (area 2); c) first variant considered in Southern Italy (area 1); d) second variant considered in Southern Italy (area 2); e) Central Italy regionalization according to Costa et al. (1995) (area 1); f) second regionalization considered in Central Italy (area 2).

Figure 4. Results of the CN analysis in Northern Italy: a) area 1; b) area 2. The arrows indicate earthquakes with $M \geq M_0$. TIPs are marked by black rectangles.

Figure 5. Results of the CN analysis in Southern Italy: a) area 1; b) area 1, considering only the shallow events; c) area 2. The arrows indicate earthquakes with $M \geq M_0$. TIPs are marked by black rectangles. The magnitude 6.9 is referred to an intermediate-depth earthquake in the Tyrrhenian sea, while the magnitude 7 (taken from the PFGING catalogue) corresponds to the Irpinia, 1980, earthquake.

Figure 6. Results of the CN analysis in Central Italy: a) area 1; b) area 2. The arrows indicate earthquakes with $M \geq M_0$. TIPs are marked by black rectangles.

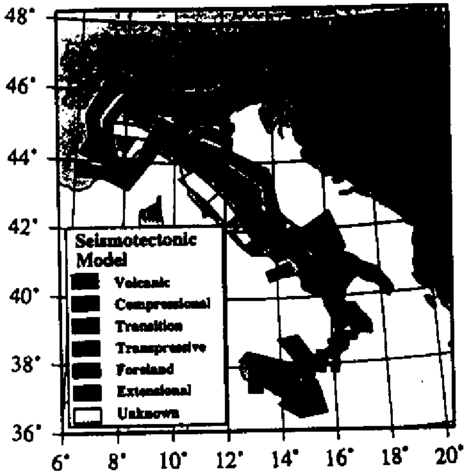


Fig.1

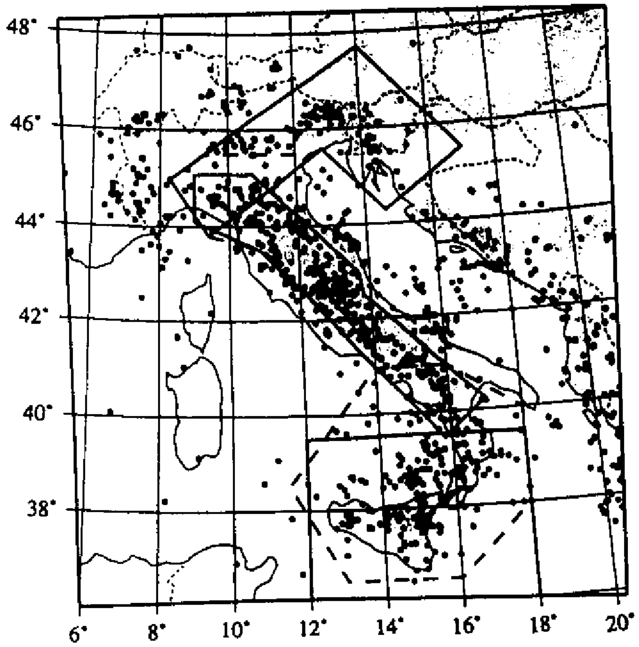


Fig.2

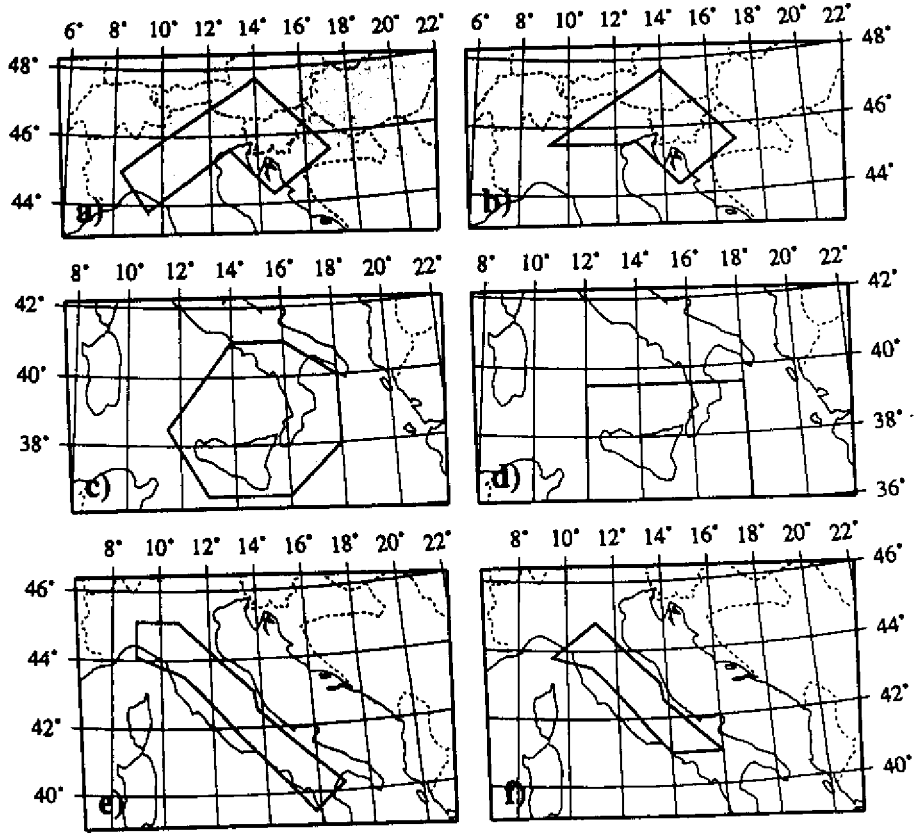
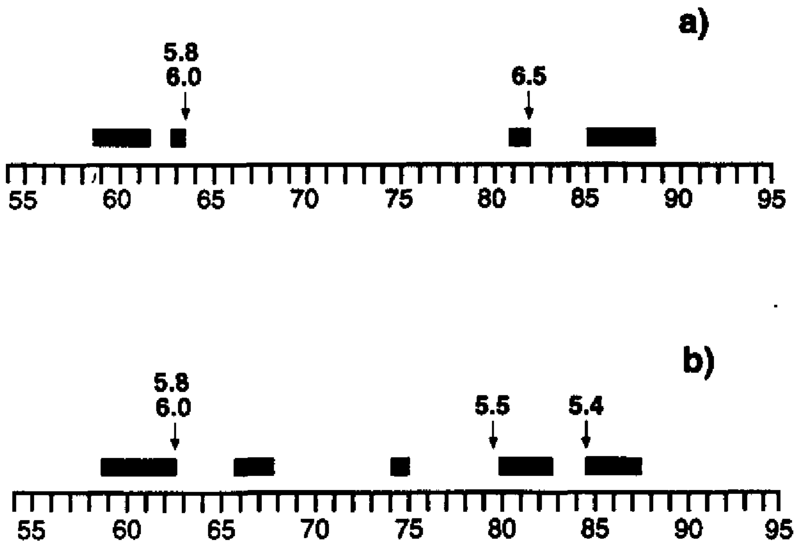


Fig.3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6.5
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b)
5.8
6.0
5.5
5.4
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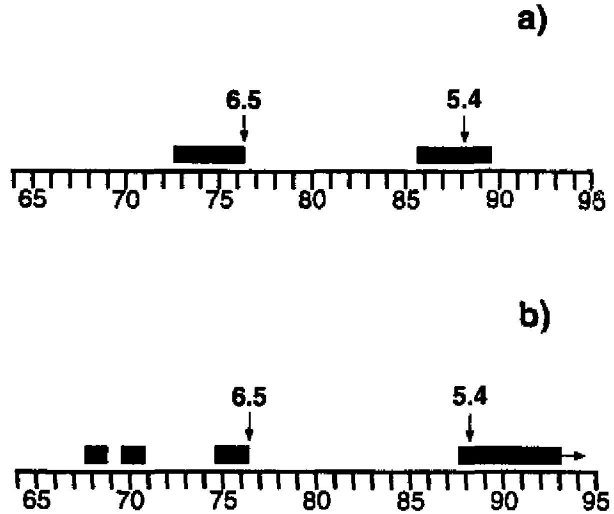
Fig.4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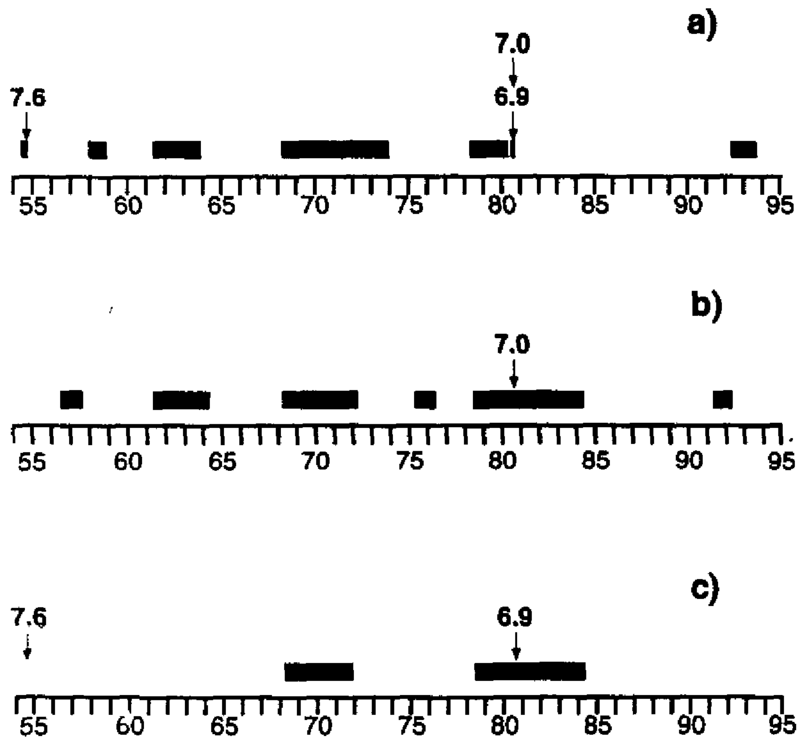
65 70 75 80 85 90 95

Fig.5


a)
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7.6
6.9
55 60 65 70 75 80 85 90 95
b)
7.0
55 60 65 70 75 80 85 90 95
c)
7.6
6.9
55 60 65 70 75 80 85 90 95

Fig.6